Lecture 3

Detector Instrumentation

Solid-state detectors

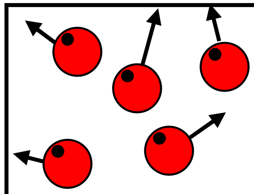
References for this lecture:.

"Semiconductor Radiation Detectors" by Gerhard Lutz, especially Chapter 2

Intel has a detailed step-by-step video procedure on how silicon chips are fabricated at:

http://www.intel.com/pressroom/kits/chipmaking/index.htm?iid=pr1_marqmain_chipmaking

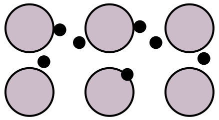
Quick primer on solid-state physics - I



GAS

Atoms move around (T)

- ➢ so inter-atomic distance large
- ➢ Individual atoms have discrete energy levels – electrons fill these up.
- ➢ Inner shell electrons are closely bound to their 'parent' atoms – hard to multiply ionize a gas atom!

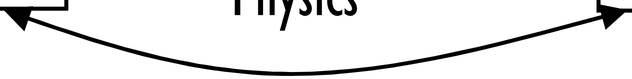


SOLID

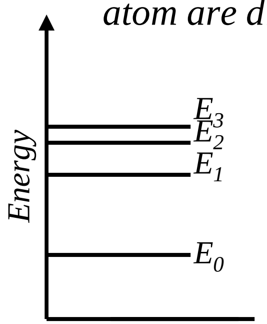
- ➢ Metal Conductor
- ➢ All atoms ionized

What holds the crystal structure together?

- ➢ Electrons are the glue
- ➢ Since electrons are free to move, applied field produces electric current.

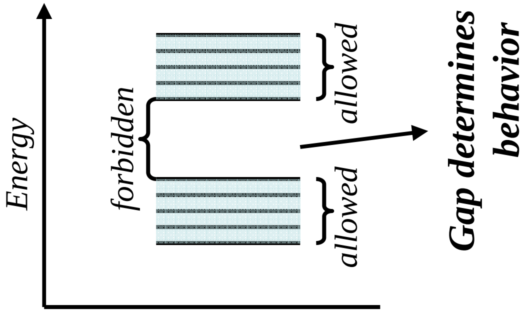


QM, energy levels of atom are discrete.

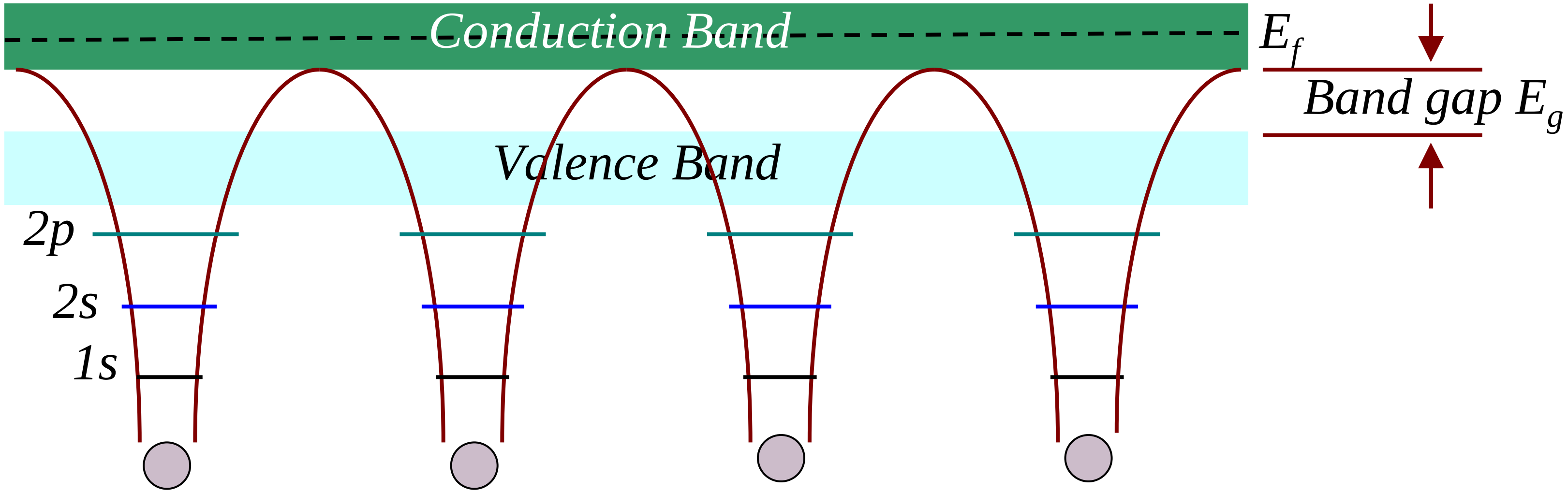


When two atoms are close together energy levels split.

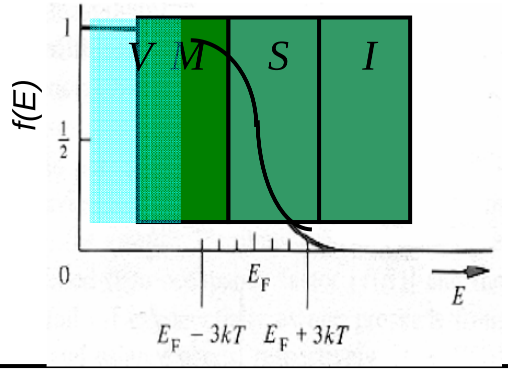
If there are a large number of atoms the discrete levels form a continuous "band".



Bands form due to closely spaced potential wells



Distribution of electrons in energy levels determined by Fermi-Dirac statistics.

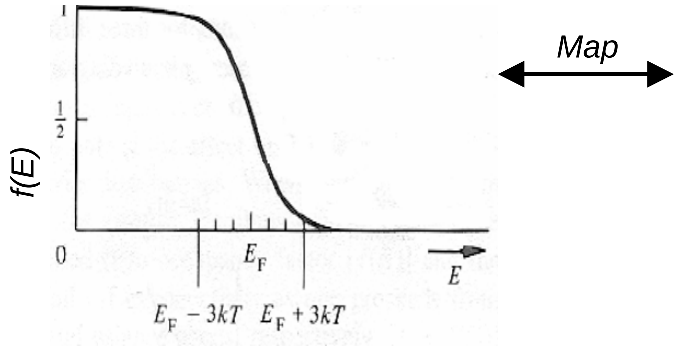


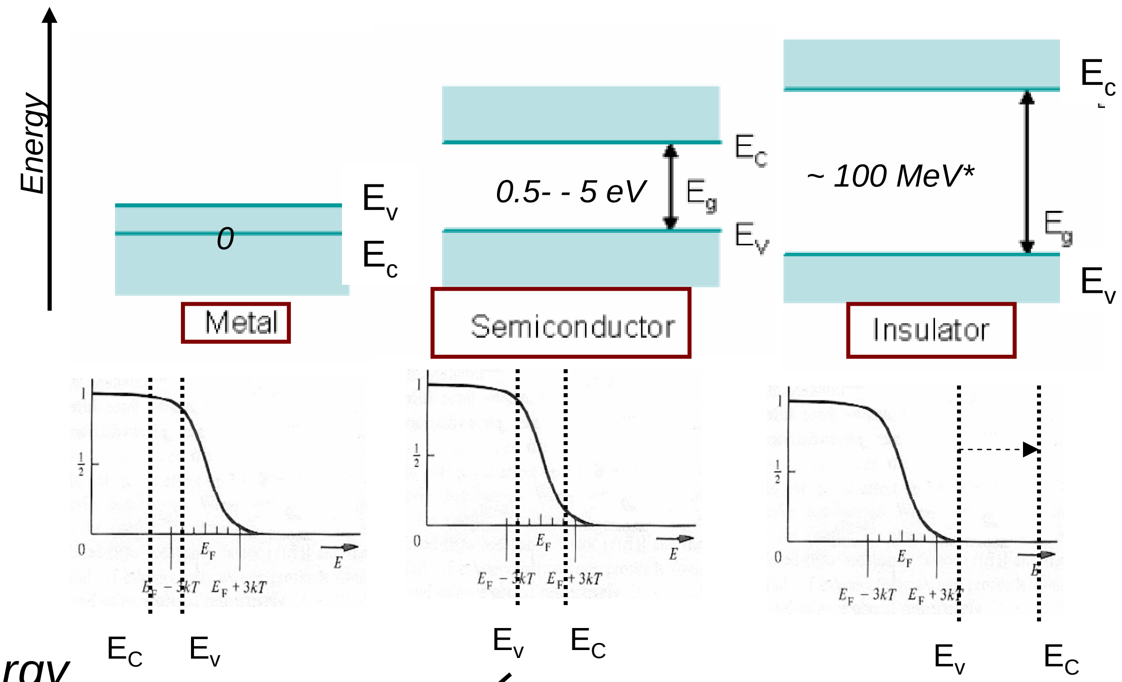
$$f(E)=\frac{1}{e^{(E-E_F)}+1}$$

Band gap determines a solid’s conductivity

E_g= Band Gap $E_{Cmin} – E_{Vmax}$

Distribution of electrons in energy levels determined by Fermi-Dirac statistics.





Electrons in the E_c ‘conduction’ energy level band are free to roam

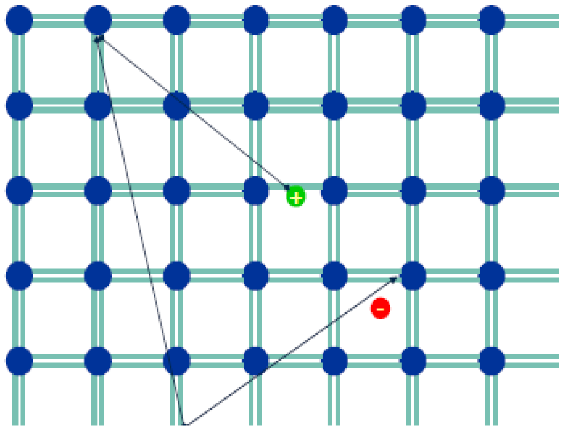
We will focus on Semiconductors: Diamond, Silicon and Germanium

Some properties of semiconductors to remember

(all units in eV)	*Diamond*	*Si*	*Ge*
E_g	*5.5*	*1.12*	*0.66*
Average energy needed to produce one e^-*/h pair*	*13*	*3.6*	*2.9*

An electron tied to the lattice in the valence band can get enough energy to kicked up into the conduction band when:

- Charged particle deposits energy
- Thermal excitation probability $\propto e^{-\frac{E_g}{k_b T}}$



Not Good !

To be used as a detector, number of charge carriers in conduction band due to MIP passage must be >> thermally produced charged carriers.

How many carriers in a semiconductor at T_{room}?

For Silicon

Band Gap $E_g = 3.6eV$;

→ *thermally generated free charge carriers at 300 K*

$n_i = B \cdot T^{3/2} \exp(-E_g/kT)$

$B = 5.23 \cdot 10^{15}\ cm^{-3} K^{-3/2}$ $k_b T = 8.6 \cdot 10^{-5}\ eV/ °K$

$\sim \underline{1.45 \times 10^{10} / cm^3}$

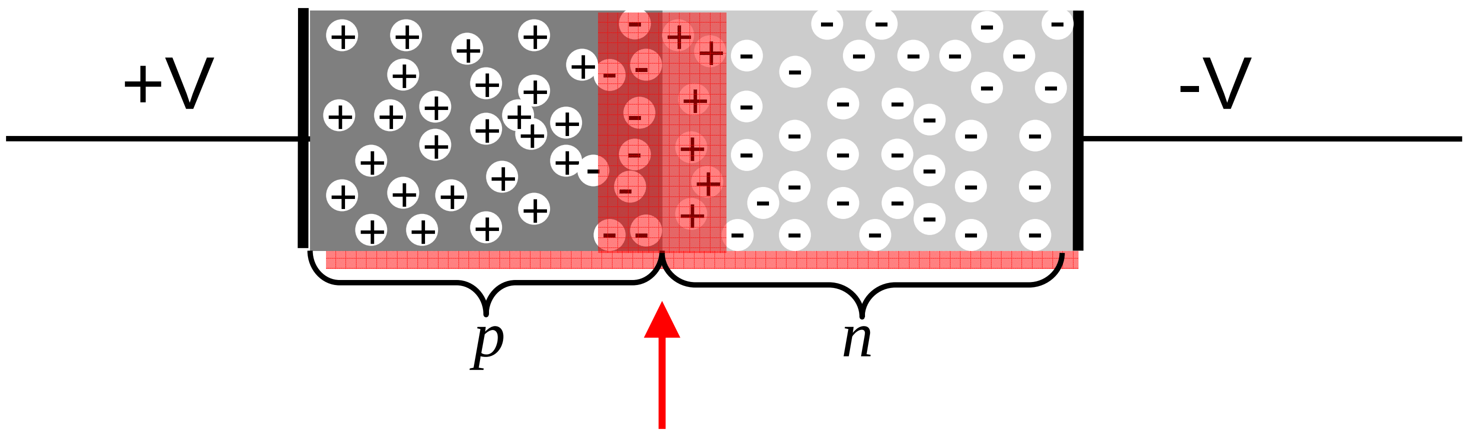
MIP deposits ~ 33000 e^-/h *pairs signal in 300µm of silicon.*

➷ *at Room temperature for 300µm thick Silicon detector:* ***S/N ~*** $\mathbf{10^{-6}}$ ☹

How can we use Silicon as a particle physics detector at room temperature ??

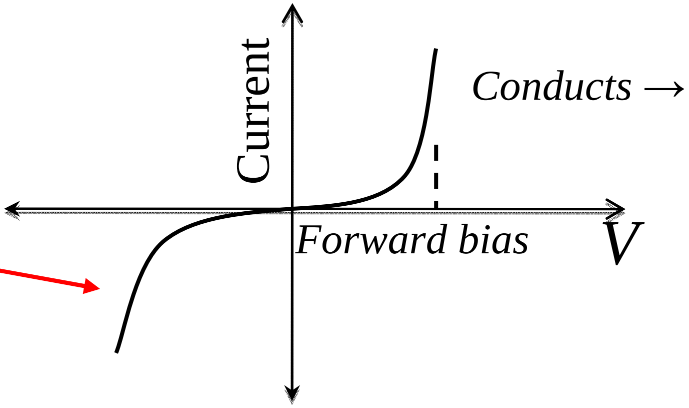
► *Need a way to block free charge carriers →* ***Doping and PN junctions***

A PN diode works by blocking free carrier flow



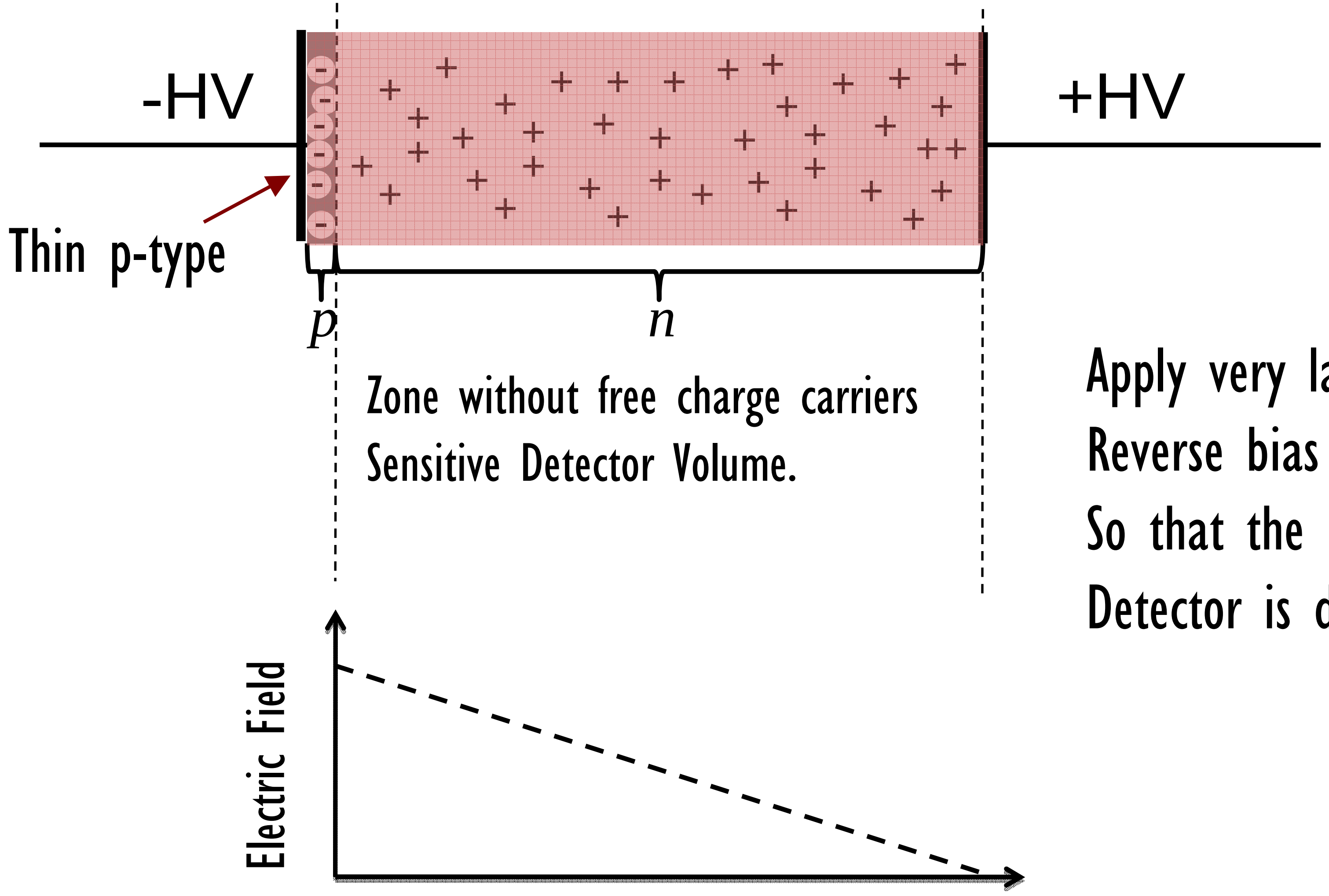
Depletion Zone at junction blocks flow of carriers across junction

Diode I-V characteristic



We are more interested in Reverse Bias

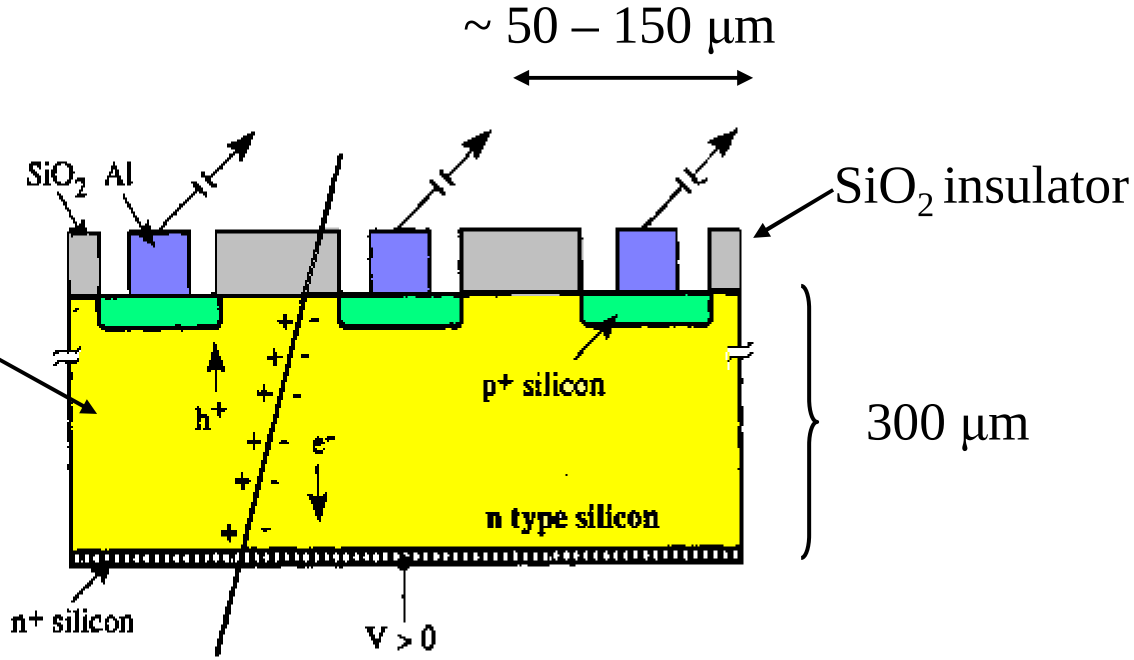
Adjust the doping and full throttle Reverse Bias



Zone without free charge carriers
Sensitive Detector Volume.

Apply very large
Reverse bias voltage
So that the bulk of
Detector is depleted.

Anatomy of a Silicon strip detector



~ 50 – 150 μm

SiO_2 insulator

Fully depleted,
Reverse biased
~ no free charge
at T=300 K

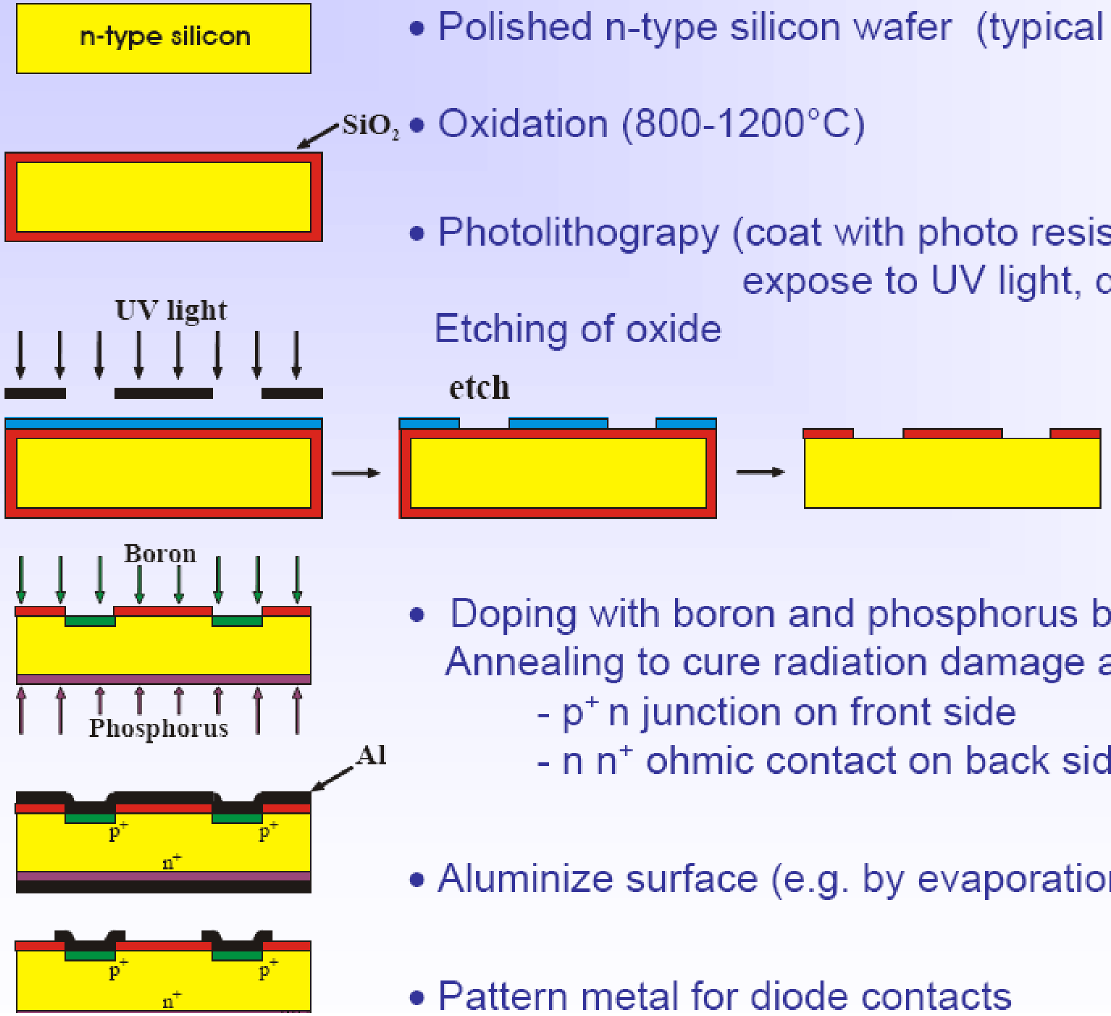
300 μm

Reverse Bias Voltage V ~ 100 V

MIP deposits about 33000 e^-/h pairs
→ position resolution down to 5 μm possible

Silicon Sensor Production

A "simple“ production sequence (schematic)



- Polished n-type silicon wafer (typical ρ ~ 1-10 KΩcm)
- Oxidation (800-1200°C)
- Photolithograpy (coat with photo resist; align mask, expose to UV light, develop photoresist); Etching of oxide
- Doping with boron and phosphorus by implantation (or by diffusion) Annealing to cure radiation damage and activate dopants
  - p^+ n junction on front side
  - n n^+ ohmic contact on back side
- Aluminize surface (e.g. by evaporation)
- Pattern metal for diode contacts

For a detailed video of how this is done, see the Intel website:
http://www.intel.com/pressroom/kits/chipmaking/index.htm?iid=pr1_marqmain_chipmaking

Signal extraction & amplification

Bias resistor

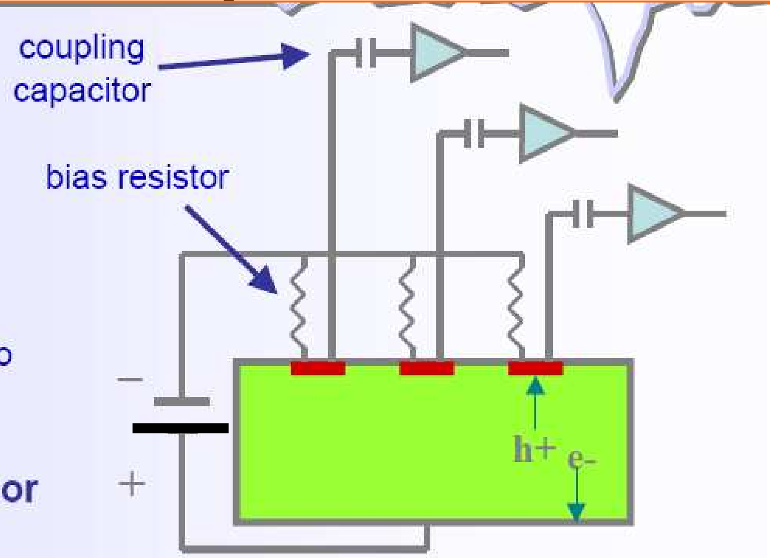
- Need to isolate strips from each other to collect/measure charge on each strip
  ⇒ high impedance bias connection (≈ 1MΩ resistor)

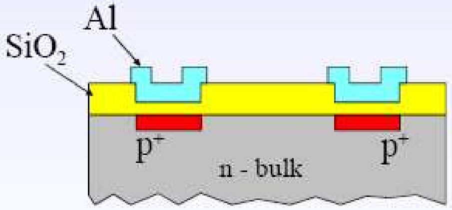
Coupling capacitor

- Couple input amplifier through a capacitor (AC coupling) to avoid large DC input from leakage current

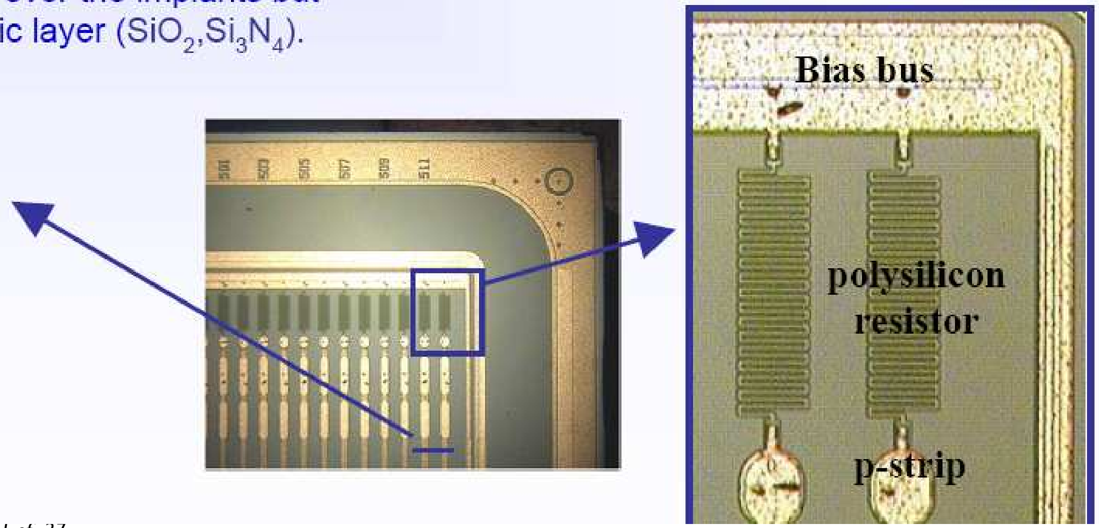
Integration of capacitors and resistors on sensor

- Bias resistors via deposition of doped polysilicon
- Capacitors via metal readout lines over the implants but separated by an insulating dielectric layer (SiO_2,Si_3N_4).





⇒ nice integration
⇒ more masks, processing steps
⇒ pin holes



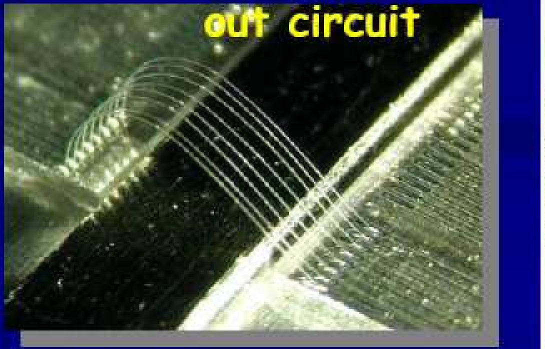
Pictures courtesy of Rainer Wallny, ALICE

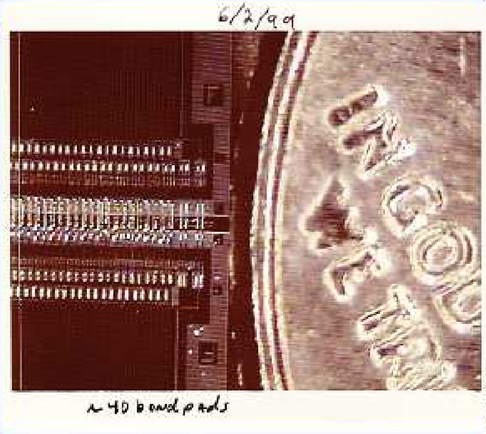
Wire Bonding

- Ultrasonic power is used to vibrate needle-like tool on top of Al wire. Friction welds wire to metallized substrate underneath.
- Pitch: 80µm pitch in a single row and 40µm in two staggered rows (typical FE chip pitch is ≈44µm).
- ≈25µm diameter aluminum wire and bond to aluminum pads (chips) or gold pads (hybrid substrates).
- Used in industry (PC processors) but not with such thin wire or small pitch.

Electron micrograph of bond "foot"

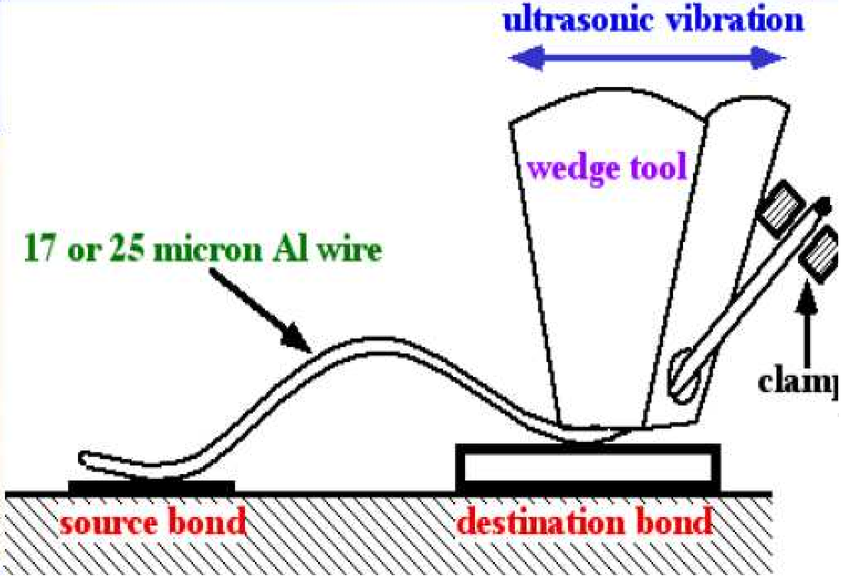
View through microscope of wire bonds connecting sensor to out circuit





6/2/99

~40 bond pads



Double sided strip detectors

Good: High resolution even with 1-dim readout

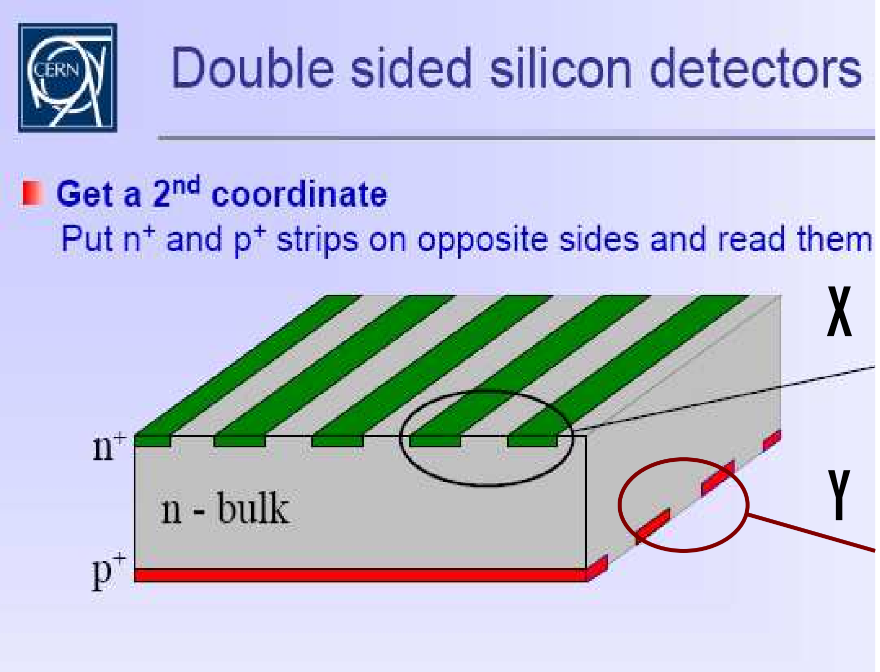
(superimpose orthogonal x- n^+ and y- p^+ strips on both sides of the n substrate) *→2n readout channnels*

Bad: Ghost tracks under high occupancy –

(x,y) co-ordinates obtained from successive closely spaced planes of a silicon are fed into a tracking algorithm that matches them up into a track.

Due to degeneracy along x and y strip, this can blow up very quickly if there are a large number of particles → *Ghost tracks*

For resolving secondary decay vertices of short lived particles (eg. Higgs – need to put the detector planes as close to the primary collision vertex as possible → high occupancy

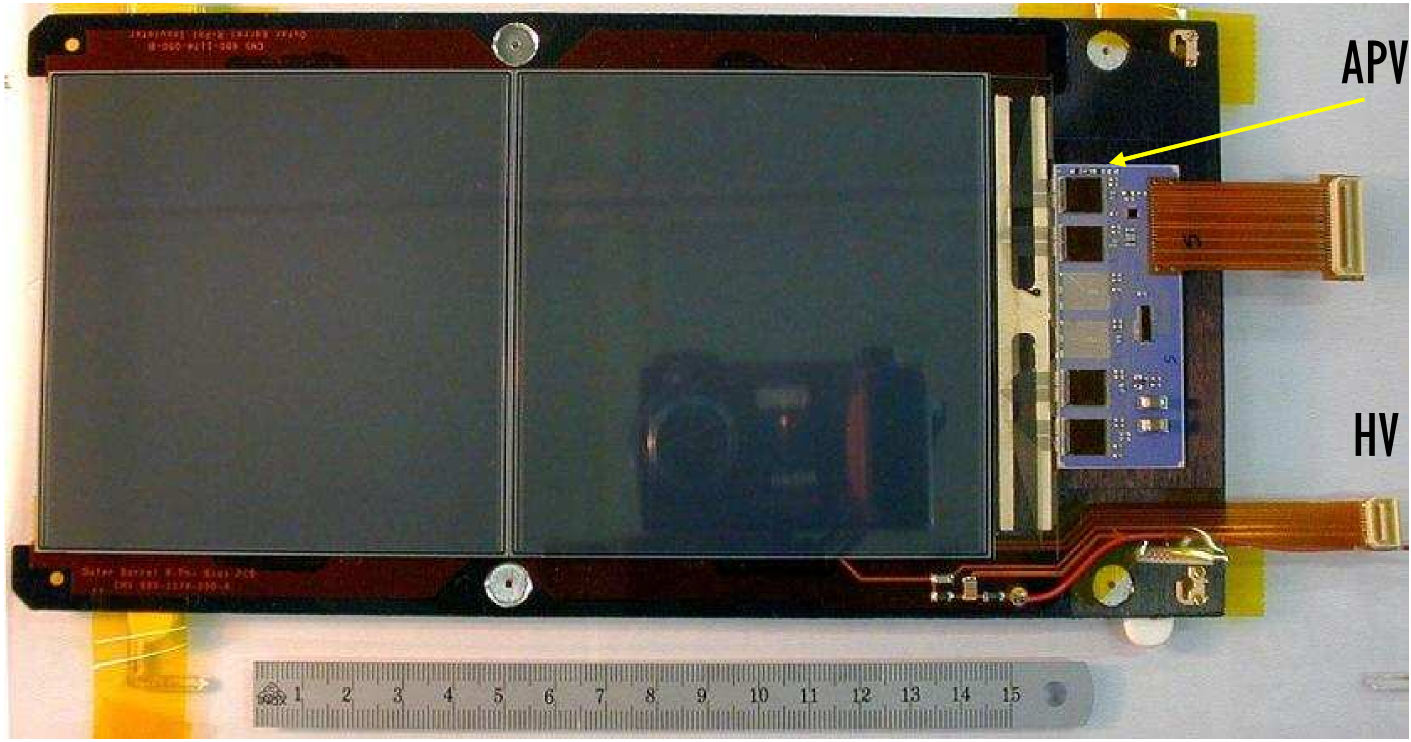


Double sided silicon detectors

- **Get a 2nd coordinate**
  Put n^+ and p^+ strips on opposite sides and read them

People are brave enough to build these

CMS Silicon Strip Detetctor Tracker module

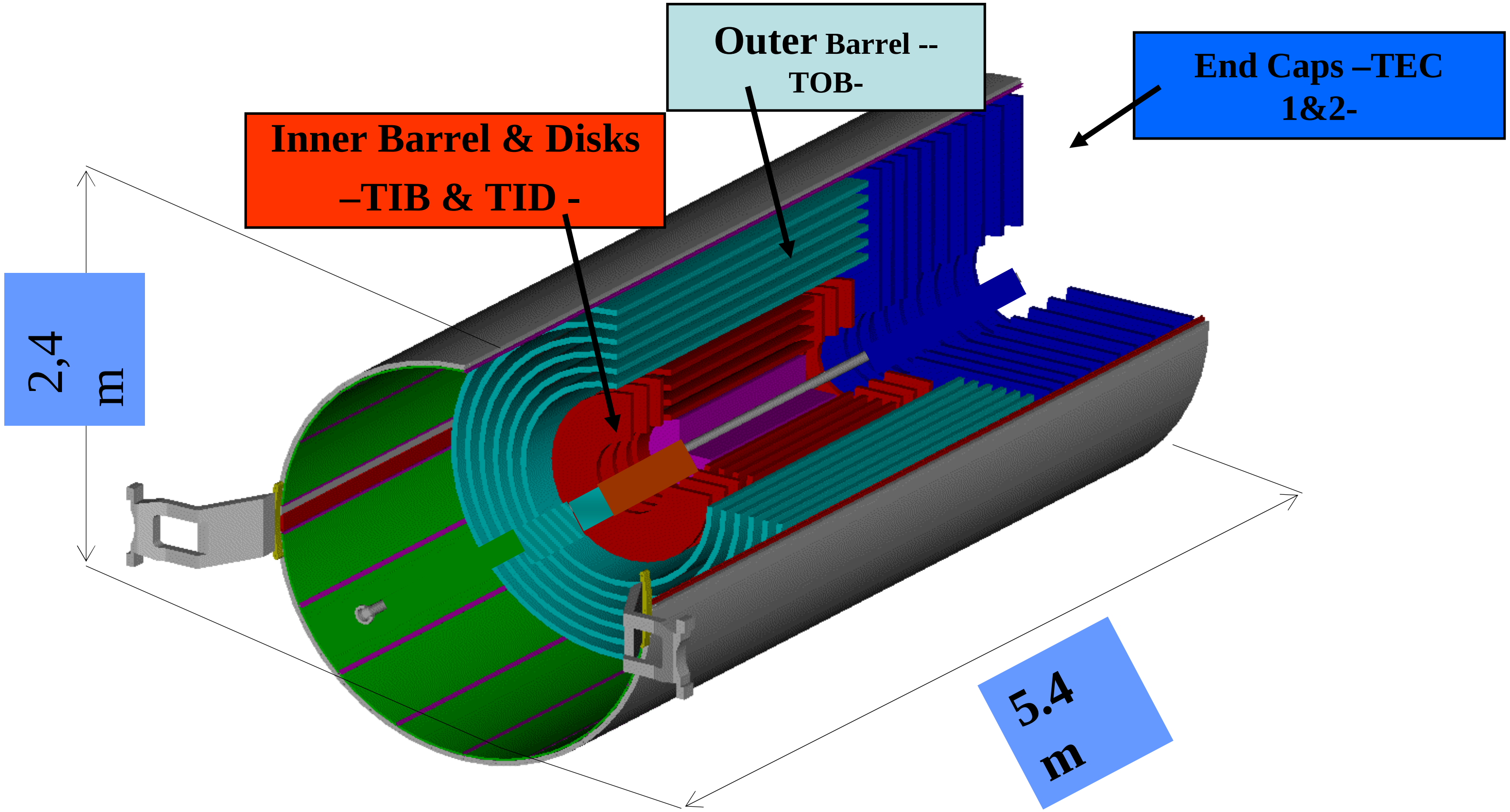


APV25 Amplifier
Chip

HV Supply

12,000 of these modules go into …

CMS Tracker Layout



Outer Barrel --
TOB-

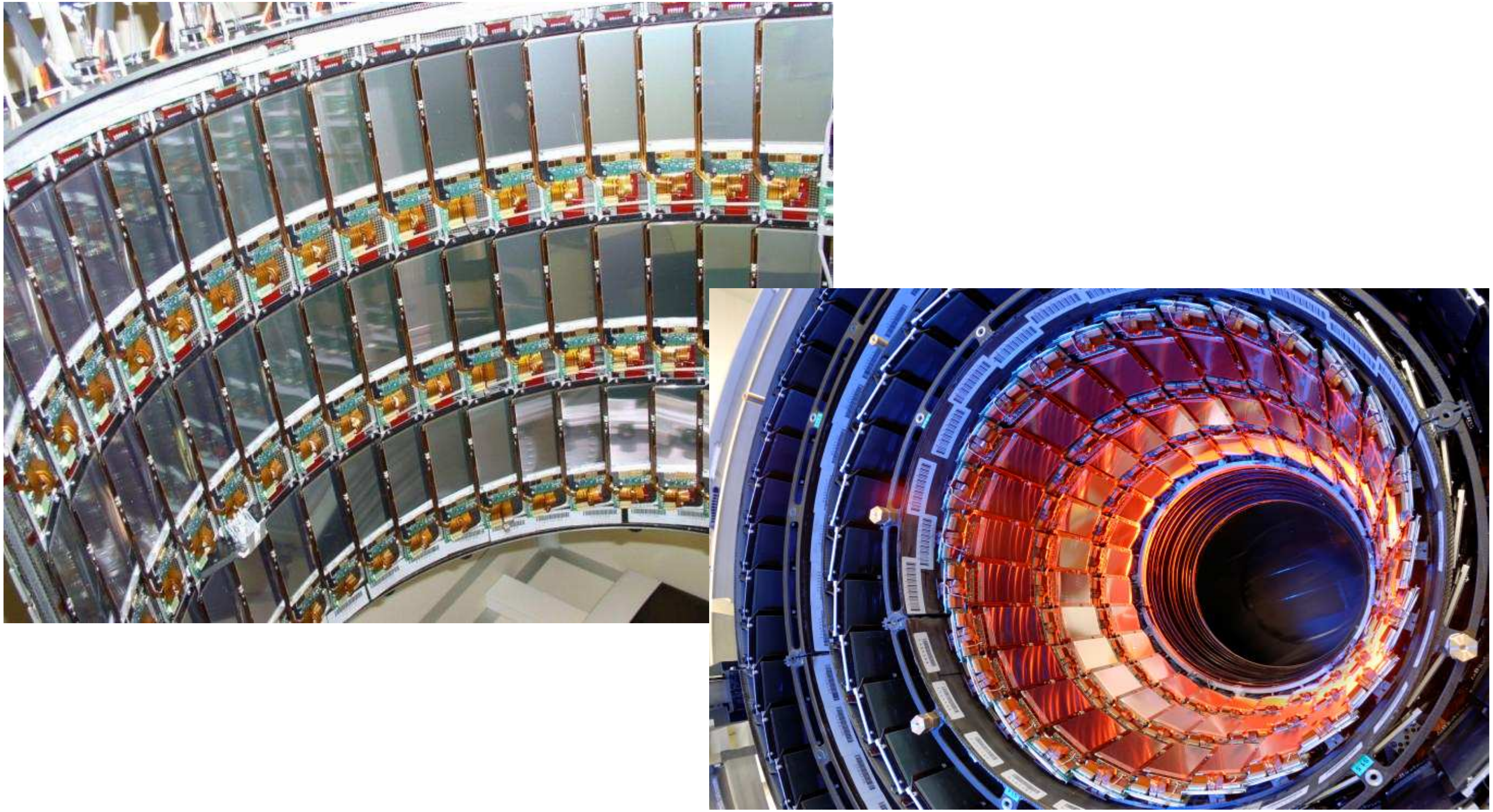
End Caps –TEC
1&2-

Inner Barrel & Disks
–TIB & TID -

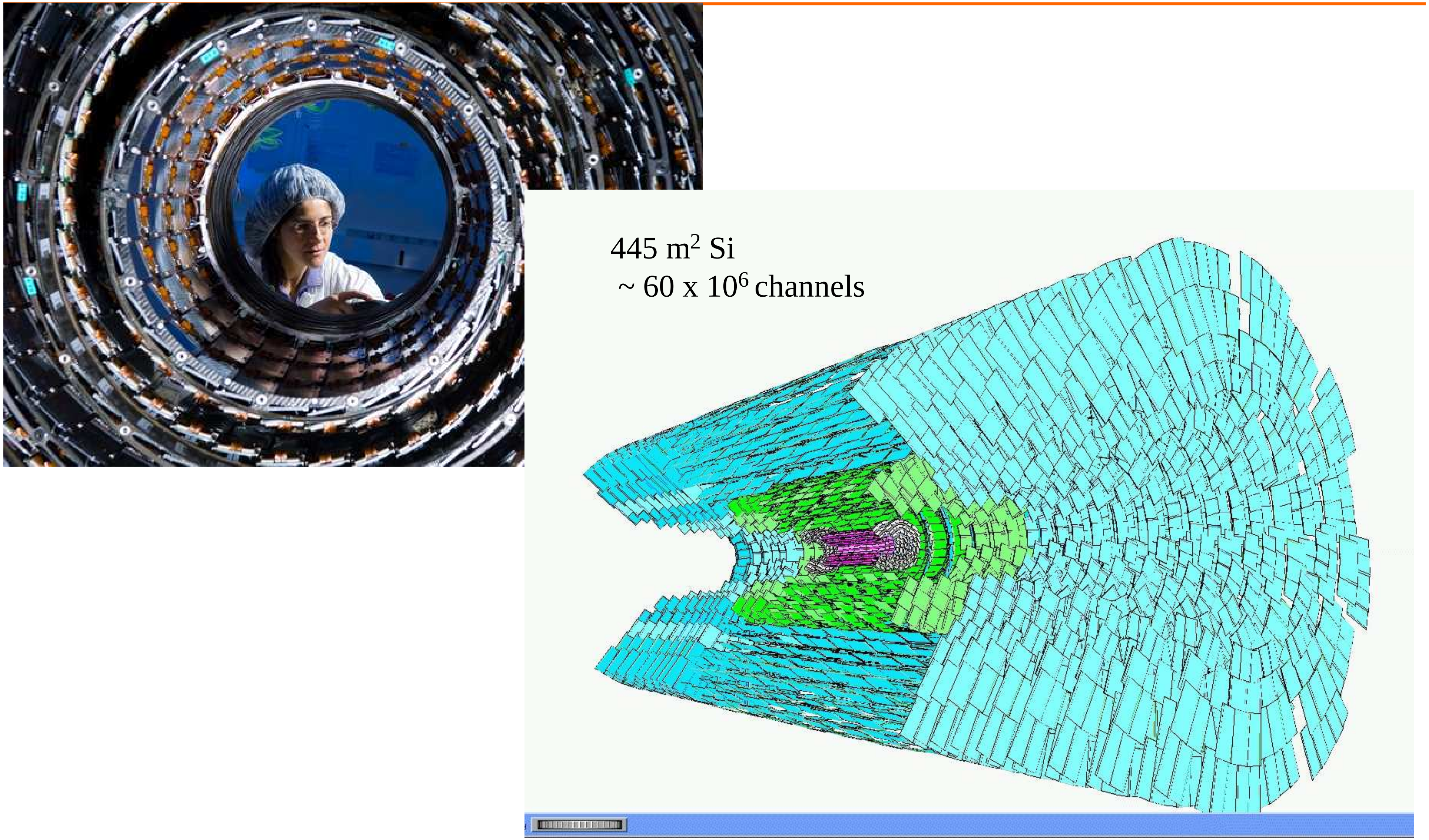
2,4
m

5.4
m

CMS Inner tracker silicon detector



CMS Inner tracker



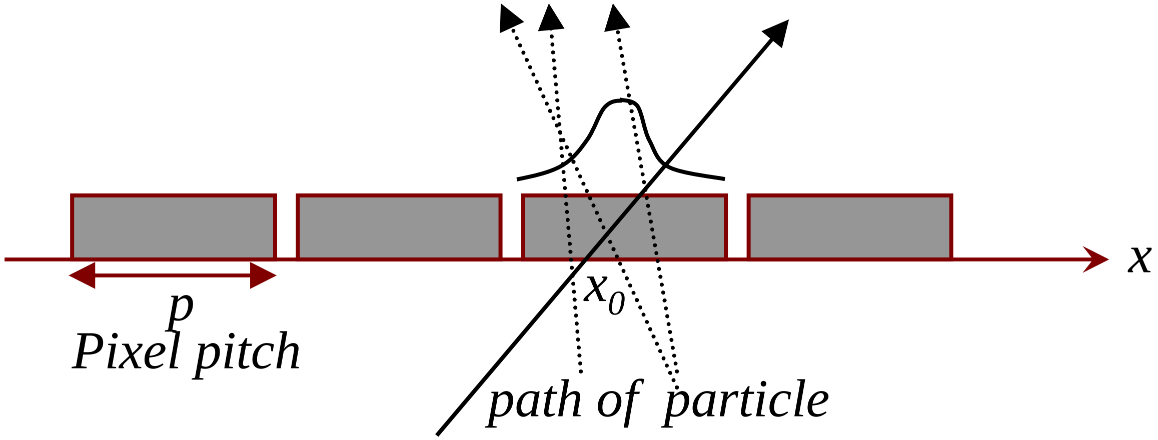
445 m^2 Si

~ 60 x 10^6 channels

What kind of detector resolution do you get for all that $$ and sweat ?

I: What is the resolution of a pixel detector?

Consider the simplified case of measurement along 1-dimension

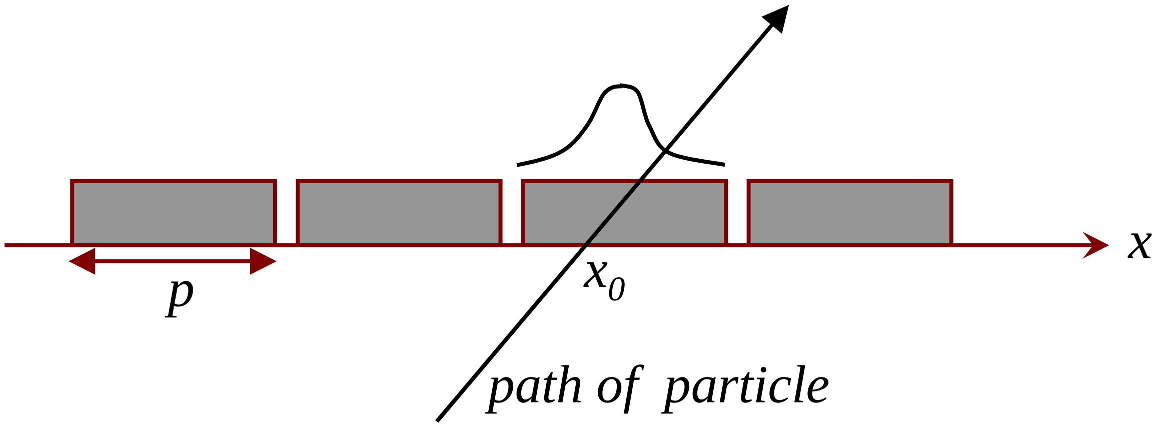


Want: exact location x_0 *where the particle went through*
…… except don't know the direction the particle came from a priori

So assume a Gaussian distribution for x_0 *within the pixel*

I: What is the resolution of a pixel detector?

Consider the simplified case of measurement along 1-dimension



The spatial resolution in dimension x is then:

$$\sigma_x^2 = \int_{-p/2}^{+p/2} \frac{x^2}{p}\,dx = \frac{p^2}{12}$$

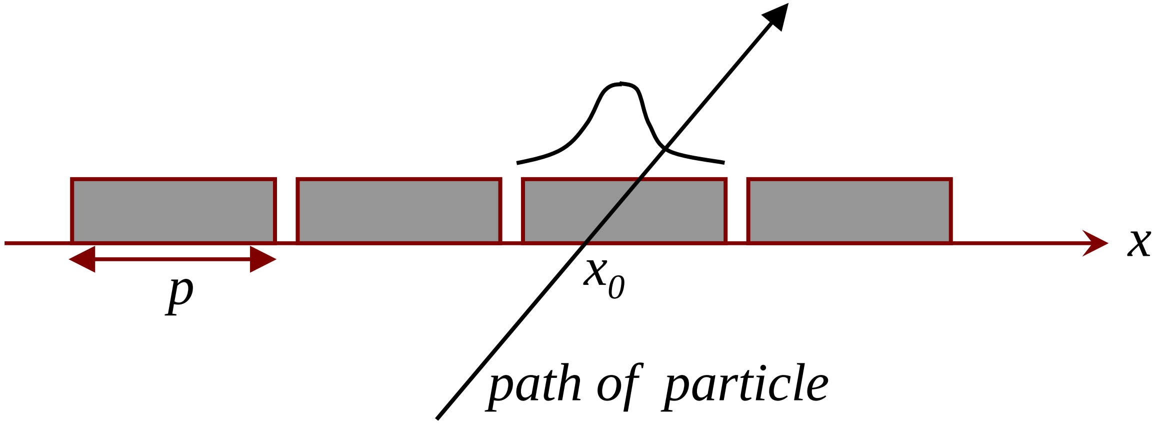
or…

$$\boxed{\sigma_x = \frac{p}{\sqrt{12}}}$$

Remember this factor: it comes for any quantization of a Gaussian distribution

I: What is the resolution of a pixel detector?

Consider the simplified case of measurement along 1-dimension

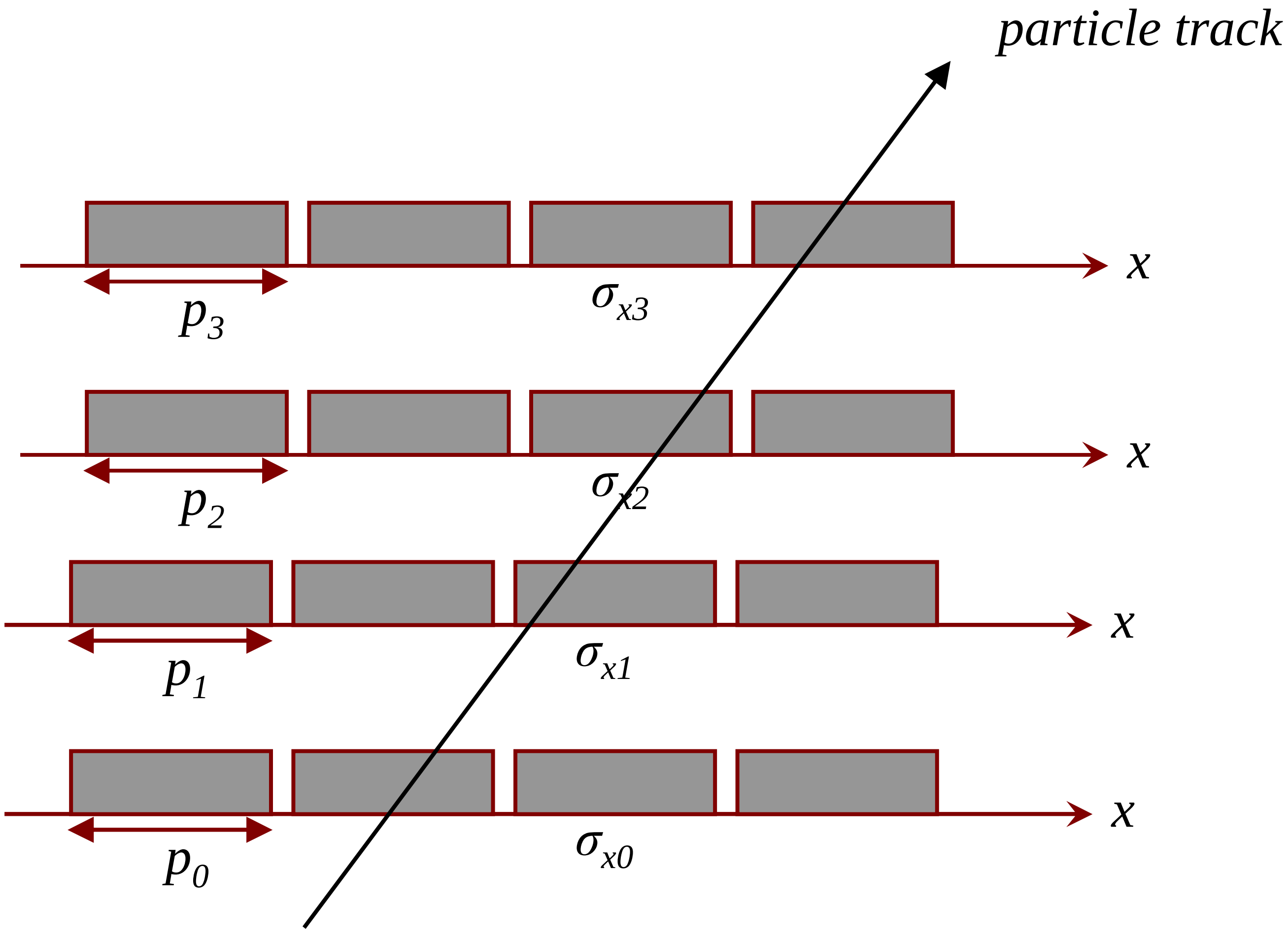


$$\boxed{\sigma_x = \frac{p}{\sqrt{12}}}$$

Eg: CMS inner tracker: **$p = 80\ \mu m \rightarrow \sigma_x = 23\ \mu m$**

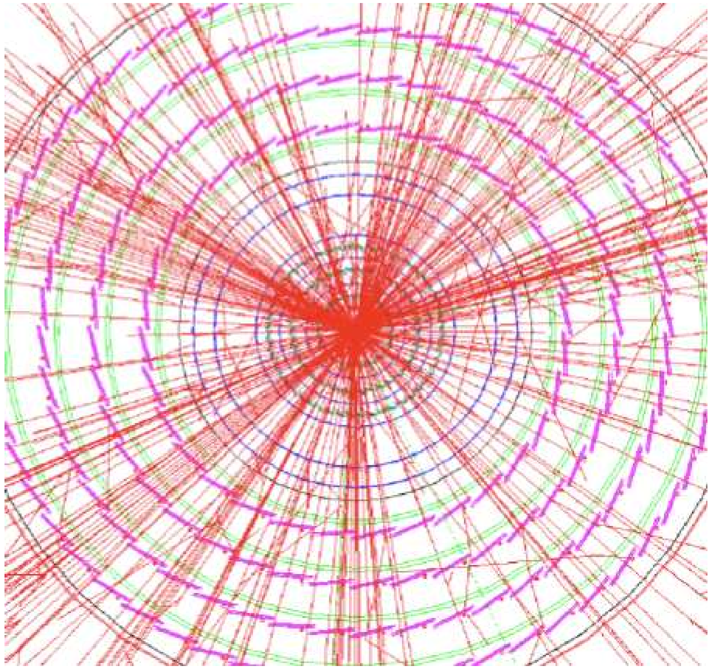
i.e. resolution less than the pitch

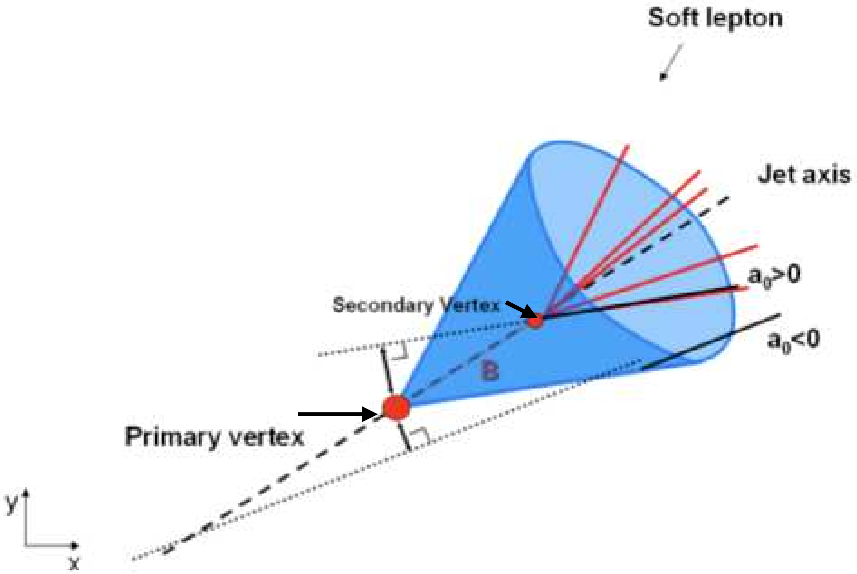
II. Tracking spatial resolution



Why is this important ?

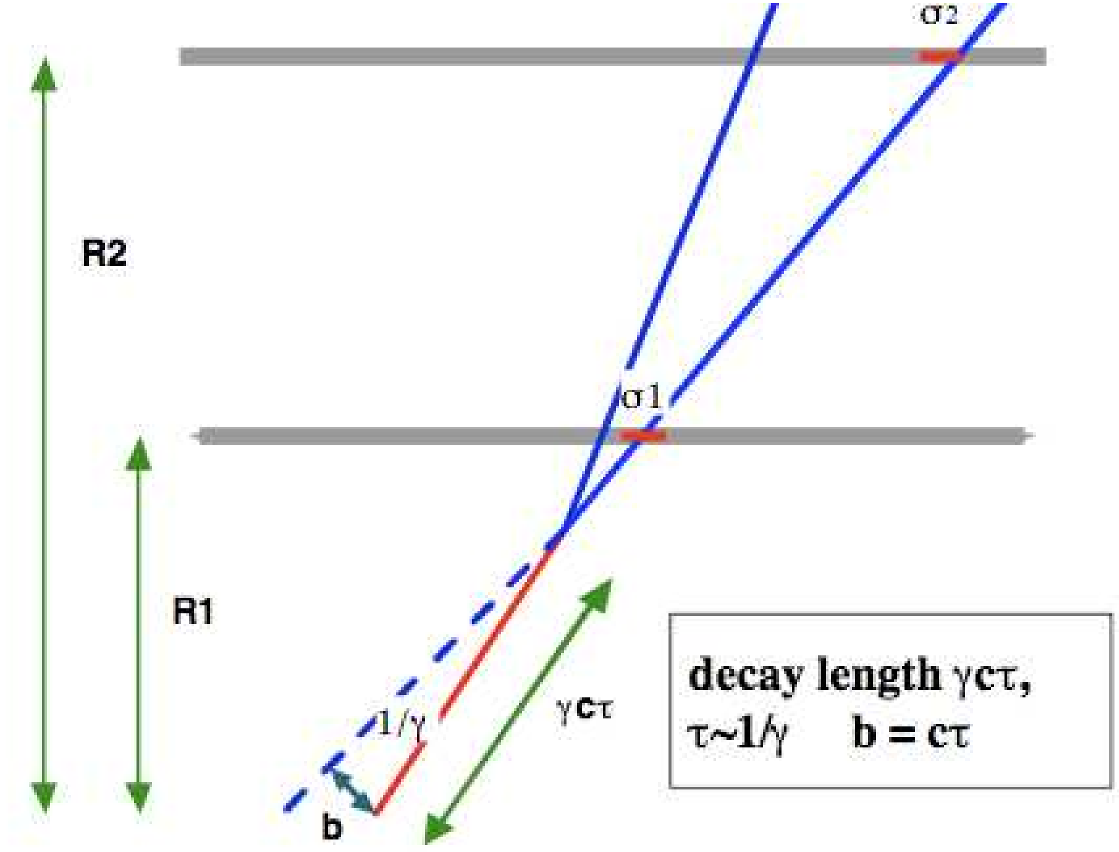
Need to reconstruct secondary vertex !





Need to resolve B:
How long a particle (Higgs?) produced in the primary collision travels before it decays

Question for Tea:
What is σ_b as function of $R_1, R_2, \sigma_1, \sigma_2$?

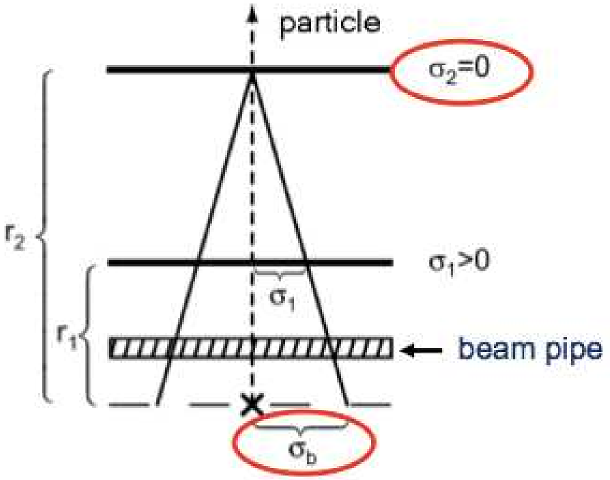


B lifetime: $c\tau \sim 450\mu m$

You may take $\sigma_1 = \sigma_2 = \sigma_d$

A simple analysis gives a simple answer:

Case 1: Set $\sigma_2 = 0$

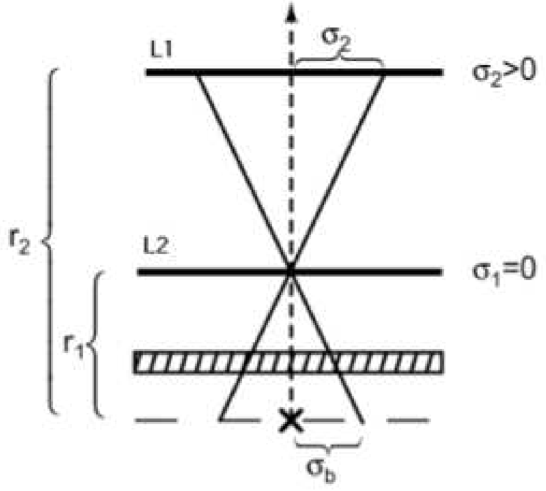


$$\frac{\sigma_b}{\sigma_1} = \frac{R_2}{(R_2 - R_1)}$$

Superpose:

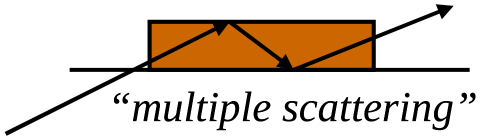
$$\boxed{\sigma_b^2 \approx \left(\frac{R_1}{R_2 - R_1}\sigma_2\right)^2 + \left(\frac{R_2}{R_2 - R_1}\sigma_1\right)^2}$$

Case 2: Set $\sigma_1 = 0$



$$\frac{\sigma_b}{\sigma_2} = \frac{R_1}{(R_2 - R_1)}$$

General formula for tracking resolution…



"multiple scattering" term for very low energy tracks at shallow angle

$$\boxed{\sigma_b^2 \approx \left(\frac{R_1}{R_2 - R_1}\sigma_2\right)^2 + \left(\frac{R_2}{R_2 - R_1}\sigma_1\right)^2 + \sigma_{MS}^2}$$

- *Usually all the σ_i's are the same*
- *So smallness of σ_b depends mostly on the first term:*
- *try to put the first plane of the detector as close as possible to the interaction (in case of CMS, R_1= 4cm ! $\sigma_i \sim 23\ \mu m$*

Summary

In this lecture:

- Principles of operation of semiconductor detectors
- Single-sided and double-sided Silicon strip detectors
- Calculation of detector resolution and secondary vertex determination